

## The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review

Article (Published Version)

Sovacool, Benjamin K, Noel, Lance, Axsen, Jonn and Kempton, Willett (2018) The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review. *Environmental Research Letters*, 13 (1). ISSN 1748-9326

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# The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review

To cite this article: Benjamin K Sovacool *et al* 2018 *Environ. Res. Lett.* **13** 013001

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## Environmental Research Letters



## TOPICAL REVIEW

## OPEN ACCESS

## RECEIVED

29 August 2017

## REVISED

26 October 2017

## ACCEPTED FOR PUBLICATION

22 November 2017

## PUBLISHED

4 January 2018

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## The neglected social dimensions to a vehicle-to-grid (V2G) transition: a critical and systematic review

Benjamin K Sovacool<sup>1,2,5</sup> , Lance Noel<sup>1</sup> , Jonn Axsen<sup>3</sup> and Willett Kempton<sup>4</sup> <sup>1</sup> Aarhus University, Aarhus, Denmark<sup>2</sup> University of Sussex, Brighton, United Kingdom<sup>3</sup> Simon Fraser University, Burnaby, Canada<sup>4</sup> University of Delaware, Newark, DE, United States of America<sup>5</sup> Author to whom any correspondence should be addressed.E-mail: [b.sovacool@sussex.ac.uk](mailto:b.sovacool@sussex.ac.uk)**Keywords:** electric mobility, sustainability transitions, vehicle to grid, vehicle grid integration, transportationSupplementary material for this article is available [online](#)**Abstract**

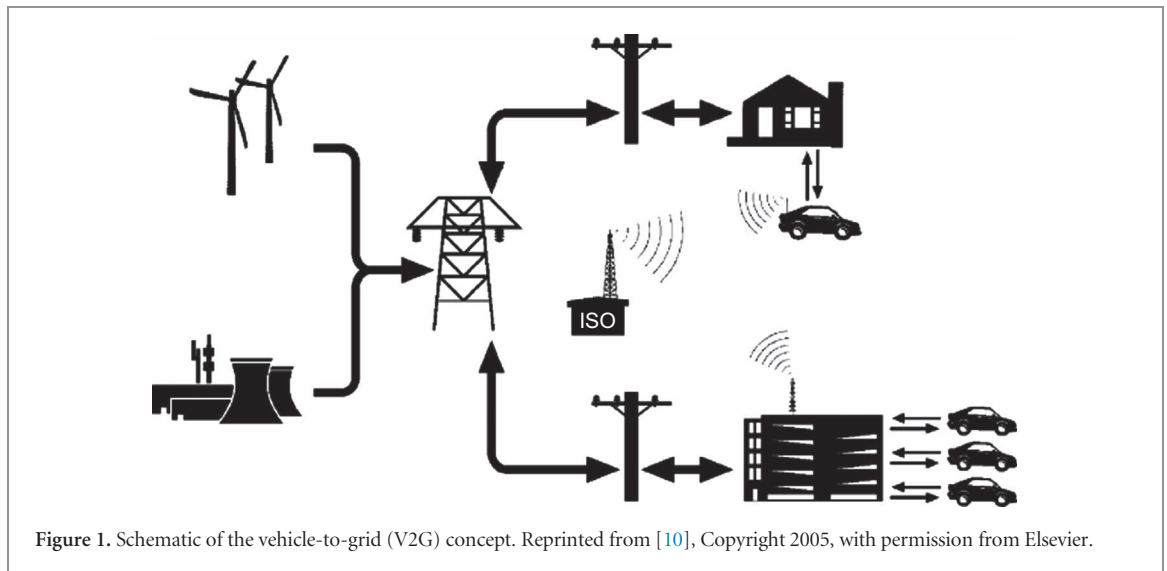
Vehicle-to-grid (V2G) refers to efforts to bi-directionally link the electric power system and the transportation system in ways that can improve the sustainability and security of both. A transition to V2G could enable vehicles to simultaneously improve the efficiency (and profitability) of electricity grids, reduce greenhouse gas emissions for transport, accommodate low-carbon sources of energy, and reap cost savings for owners, drivers, and other users. To understand the recent state of this field of research, here we conduct a systematic review of 197 peer-reviewed articles published on V2G from 2015 to early 2017. We find that the majority of V2G studies in that time period focus on technical aspects of V2G, notably renewable energy storage, batteries, or load balancing to minimize electricity costs, in some cases including environmental goals as constraints. A much lower proportion of studies focus on the importance of assessing environmental and climate attributes of a V2G transition, or on the role of consumer acceptance and knowledge of V2G systems. Further, there is need for exploratory work on natural resource use and externalities, discourses and narratives as well as social justice, gender, and urban resilience considerations. These research gaps need to be addressed if V2G is to achieve the societal transition its advocates seek.

**1. Introduction**

Globally, the transportation sector remains significantly dependent on fossil fuels, with an array of sobering, negative environmental and social impacts. To decarbonize this sector, the International Energy Agency suggests that plug-in electric vehicles must make up at least 40% of new vehicle sales globally by 2040 to be on track to stabilize greenhouse gas concentrations at 450 ppm [1]. Others similarly argue that diffusion of plug-in electric vehicles (PEVs), including plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs), at a similar or even more ambitious scale or scope is necessary to achieve deep greenhouse gas (GHG) reduction targets [2–4].

Nonetheless, the acceptance and adoption of PEVs will invariably impact electricity grids due to increased electricity demand and the temporal shifting of demand

peaks—offering both benefits and risks to electricity systems. Over the past two decades, researchers have explored various notions of intelligently integrating grid operations with PEVs, including terms such as vehicle-to-grid [5, 6] (V2G), grid-integrated vehicles [7] (GIV), and vehicle-grid-integration (VGI) [8]. These connected concepts describe efforts to link transportation and electricity systems in ways that may provide synergetic benefits to both. VGI has more recently developed as a sort of umbrella term to encompass unidirectional integration efforts, such as ‘smart’ or ‘controlled’ charging (now sometimes called V1G), as well as bidirectional integration, namely V2G. However, in this paper we utilize V2G because it reflects the most commonly applied term in the literature. Technically, a V2G configuration means that personal automobiles have the opportunity to become not only vehicles, but mobile, self-contained resources that can



manage power flow and displace the need for electric utility infrastructure (see figure 1). They operate as vehicles when drivers need them but switch to become power sources or opportunities for energy storage during peak hours, recharging at off-peak hours such as later at night [9]. However, the literature often confuses V2G with other types of vehicle-grid-integration.

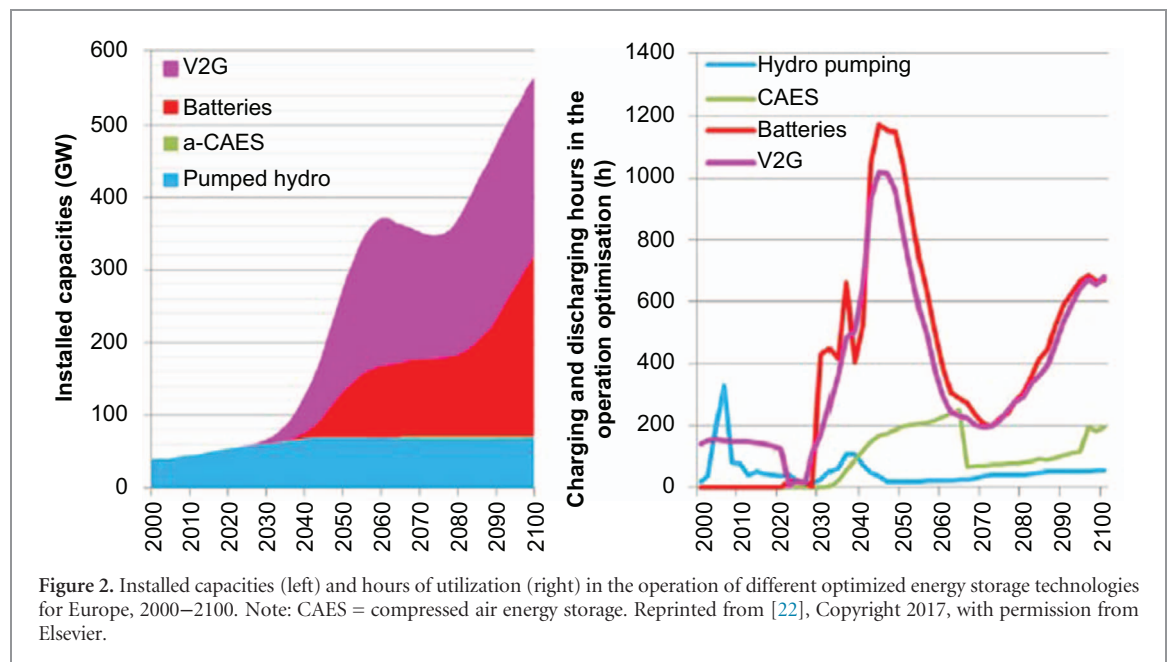
Nevertheless, V2G has the potential to offer benefits to a diverse mix of important stakeholders. For electric utilities, V2G can provide back-up power, support load balancing, reduce peak-loads [11, 12], reduce the uncertainty in forecasts of daily and hourly electrical load, [13] allow greater utilization of existing generation capacity [14, 15] and of distribution infrastructure [16]. For governments seeking to slash harmful emissions, V2G can help integrate intermittent renewable electricity generation into the grid [17] by using renewable energy when it is available [18, 19], on top of the climate change mitigation implications of electrifying vehicles. If the value created by V2G is used to incentivize PEV ownership, it could further reduce emissions in the transportation sector [20, 21]. In turn, widespread V2G deployment could benefit PEV buyers, electricity rate payers, and society more generally.

The potential shift to V2G—in terms of adoption and impact—could therefore have vast advantages. One assessment simulated the future penetration of decentralized, flexible power systems (including renewable energy and storage) and concluded that V2G offered the *most storage* potential in Europe compared to other options such as standalone batteries, compressed air energy storage, or pumped hydro (see figure 2)[22]. Another study calculated that V2G-enabled PEVs could provide much needed assistance to transmission operators in the United States as they maintain reliability and operating standards, and it estimated the value of those services at up to \$12 billion per year, some of which would flow to PEV owners [10]. A 2016 study by the Transportation Research Board reported that vehicle-to-infrastructure (V2I) systems,

where vehicles utilize communication devices to share information with the components that support national highway systems, could be utilized by about 460 million vehicles globally by 2030; vehicle-to-retail (V2R) systems, where cars communicate directly with fuel or automotive parts retailers, by another 406 million vehicles by 2030 globally; and another 50 million vehicles globally offering active V2G services by 2030 [23].

Although V2G therefore represents an enticing idea with many purported benefits, it nonetheless remains in the pilot project stages of development. Among the first projects was one conducted at University of Delaware, where managers used 23 personal vehicles, consisting of Mini-E's, modified Scion xB's, and an experimental Honda Accord, to provide frequency regulation for the PJM Interconnection, starting in 2009 [24]. Meanwhile, in Japan, Nissan tested a vehicle-to-building project in a building office in Atsugi City in 2013, consisting of six Nissan Leafs to reduce summer peak loads, and resulting in a savings of 500 000 yen per year [25]. In California, the Department of Defense is currently (as of 2017) testing the use of 20 person vehicles to provide V2G services, including both renewable energy integration and ancillary services at the Los Angeles Air Force Base, starting in 2013 [26]. Beginning in 2016, Denmark also has a project consisting of ten e-NV200 electric vans in the city of Fredericksburg providing V2G services to the Danish grid [27]. Finally, also starting in 2016, in the United Kingdom, Nissan, Enel, and National Grid have agreed to set up a trial to test one hundred V2G units, including both Nissan Leafs and e-NV200 electric vans [28].

Thus, V2G research remains at a critical juncture—some proponents and researchers believe it could facilitate or at least complement a shift in electric mobility with potentially voluminous social, economic, and environmental benefits, but it remains at a nascent stage of technical development. Sovacool *et al* provide a recent socio-technical review of V2G-related literature



and offer a potential critical research agenda to move forward, but their approach was non-systematic and more qualitative [29]. Building from that piece to better systematize where the field currently is, and where it should go, in this paper we offer a critical review of almost two-and-a-half years of V2G recent research. Following a methodology outlined in the second section of the paper, we systematically searched for, and then coded, 197 peer-reviewed studies published over the 28 months of January 2015–April 2017 across 15 academic databases. We examined each paper for topic and method, as well as each author's discipline, region and gender.

As figure 3 summarizes, this body of research involved 659 authors, 359 disciplines, and 200 different research designs/methods. It was mostly dominated by a discussion of technical elements such as renewable energy storage, grid services, batteries, and smart charging. Research largely neglected more environmental elements such as air pollution and greenhouse gas emissions, and social elements such as users, attitudes, perceptions, and driving behavior. The majority of researchers were in science and engineering, which accounted for almost 80% of the authors, who were also mostly men (about 83% of cases where sex could be determined by the author's name)—a finding that bears greater salience when one reads our section on gender norms. Research methods were based primarily on technical simulations or quantitative modeling, which accounted for almost 60% of those employed across the sample of studies.

In this review, we briefly summarize the main insights offered by the V2G literature, a body of work that mostly emphasizes technical aspects. We then argue for the importance of assessing some of the neglected social elements of a V2G transition, specifically the environmental performance of V2G systems, financing and business models, natural resources, and

the role of consumer acceptance and knowledge, as well as the need for discourse analysis, social justice assessments, evaluating gender norms, and examining urban resilience.

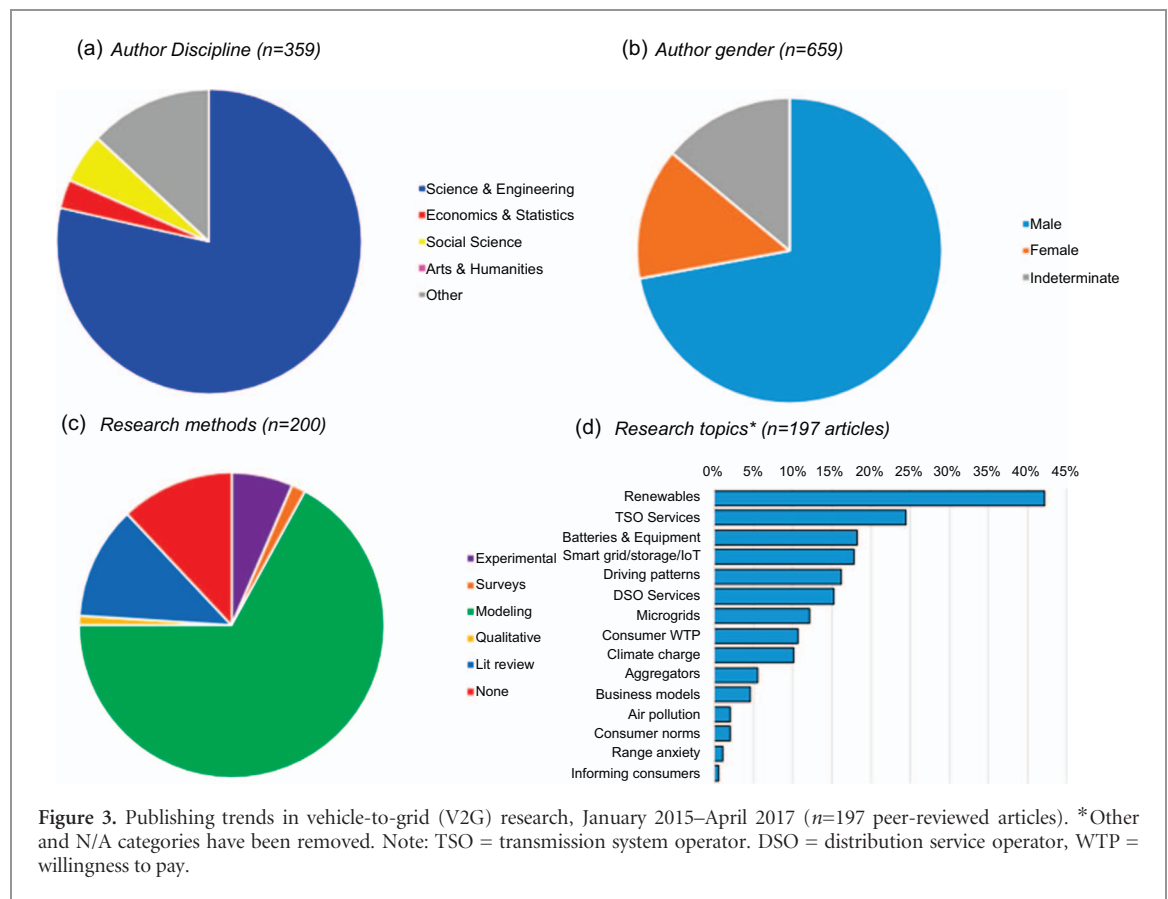
## 2. Research method: a systematic literature review

To collect data for our study, our primary method was a qualitative systematic review. Systematic reviews differ from integrative reviews, rapid evidence assessments, and purely qualitative or narrative reviews [30]. A systematic review utilizes repeated searches or iterations of the research question in order to identify studies that cover a large bodies of evidence, especially those that may involve different research designs or combine qualitative and quantitative data [31]. A review becomes 'systematic' when it is based on a clearly formulated question or topic, identifies relevant studies, appraises their quality or relevance and then summarizes their evidence. As Khan *et al* note, 'It is the explicit and systematic approach that distinguishes systematic reviews from traditional reviews and commentaries' [32].

Systematic reviews are intended to serve as a more robust alternative to traditional, narrative, or non-systematic reviews which generally:

- Lack thoroughness or comprehensiveness;
- Lack a means for making sense of what a large body of evidence is saying;
- Can be biased by the researcher;
- Can lack rigor or replicability [33].

Systematic reviews therefore attempt to improve the evidence base for analysis by enabling better specification and inclusion of a broader range of results (minimizing bias), enhanced transparency about the



research process, and offering a research design that can be replicated [34, 35].

Most systematic reviews are quantitative, such as meta-analyses completed in the the health or medical literatures, which aim to establish a hierarchy of evidence that can be used to promote both evidence based practice and improve the effectiveness of research [36]. Qualitative systematic reviews proceed differently, but in doing so offer a distinct set of advantages. Qualitative systematic reviews enable the exploration of questions that cannot be explored or explained by experimental designs or randomized controlled trials—frequently the case in social sciences and arts and humanities research. Qualitative systematic reviews are also well suited to topical areas where:

- Both positivist and interpretive perspectives are utilized and can be incorporated;
- Low consensus over research questions exist;
- Experimentation may or may not be feasible;
- Researchers are concerned with why something works or does not work and the context in which this occurs;
- Multiple and competing extraneous factors may be at play, and the balance between them may change over time [33].

This is certainly the case with V2G research, given that:

- Both quantitative and qualitative methods continue to be utilized;
- Research questions vary considerably in scale and scope;
- Experimental or quasi-experimental research designs are rare;
- Researcher questions remain equally concerned with technology and social context;
- Complex factors are at play with rapid changes in technical performance, regulations, and consumer attitudes.

We maintain that this makes V2G research well-suited for a qualitative systematic review.

To conduct this review, we proceeded in four stages. The *first stage* involved the crafting of our research questions and topics: our aim was to broadly assess the state of the V2G field, that is, to look at trends in authorship (discipline, region, gender), methods, case studies, and themes. We therefore kept our selection criteria broad and inclusive to any study published on the topic of V2G, from any discipline, employing any method, from any location, published in English.

The *second stage* involved our selection of articles and time frame. As Popay *et al* [36] note, the key standard of assessment in sampling for systematic reviews is ‘Does the sample produce the type of knowledge necessary to understand the structures and processes within which the individuals or situations are located?’ We therefore decided to search for



peer-reviewed academic articles on V2G published January 2015–April 2017, a period of 28 months. We chose this recent time period given how rapidly advances in technology and innovation continue to lower cost and/or improve performance, making even studies published five years ago relatively out of date. The idea was to create a comprehensive, systematic, timely review to reveal the state of the art within the V2G research community.

The *third stage* was to determine our coding strategy or analytical protocol for assessing the literature. We decided on a mix of quantitative and qualitative aspects with a mix of closed and open categories. The fixed or closed ended categories of coding centered on (1) author discipline, (2) author location/region, (3) author gender, (4) method/research design, and (if applicable) (5) case studies. The final category (6) was open ended and emphasized themes or topics. Admittedly, this process was co-created and interactive with the fourth stage (below) in that we modified some of our coding criteria as we analyzed the literature, expanding categories to better fit with the themes in the literature, especially for the more open-ended category of ‘theme’ or ‘topic.’ For more details about these aspects of the review, see the supplementary material available at [stacks.iop.org/ERL/13/013001/mmedia](https://stacks.iop.org/ERL/13/013001/mmedia).

The *fourth stage* was our selection and analysis of literature. We searched 15 different academic databases, looking for several sets of keywords within full-length, English-language research articles. We searched article titles, abstracts, keywords, and full texts for the terms ‘vehicle-to-grid’ and ‘vehicle-grid integration,’ as well as the abbreviations ‘V2G’ and ‘VGI,’ across the following academic databases:

- Nature Publishing Group (home to *Nature* journals)
- American Association for the Advancement of Science (home to *Science*)
- National Academies of Science (PNAS, National Research Council reports)
- American Chemical Society (journals such as *Environmental Science and Technology*)
- Royal Society of Chemistry (journals such as *Energy & Environmental Science*)
- ScienceDirect (Elsevier journals such as *Energy*, *Energy Policy*, and *Applied Energy* as well as *Transport Policy* and *Transportation Research Parts A-E*)
- JSTOR (social science journals)
- Project Muse (social science journals)
- Hein Online (law and legal studies)
- PubMed (medicine and public health)
- SpringerLink (business and area studies)
- Taylor Francis/Routledge Informaworld (business and area studies)
- Wiley Blackwell (area studies)

- Sage (area studies)
- EBSCOhost (environment and geography).

This resulted in 240 distinct searches (four terms, four fields per 15 databases) that culminated in 227 studies that were then narrowed down to a final sample of 197 studies based on relevance; these 197 studies formed the basis for our review. Table 1 provides an overview of the results.

At least six limitations to our overall research design deserve mentioning. First, we looked only at published articles, rather than those submitted, under review, or rejected. Second, we examined only full-length, peer reviewed material, thus excluded editorials, book chapters, or other formats. Third, we collected only English language sources, excluding some French, German, and Chinese articles. Fourth, we focused on only recent or timely material, not necessarily the groundbreaking, original pilot projects, or formative works in the field, or necessarily the most innovative works. Fifth, these databases are not the only place academic work on V2G is ongoing; multiple conference proceedings, along with some databases of journals (such as those published by the Multidisciplinary Digital Publishing Institute), have been excluded. Sixth, as we wanted to investigate the V2G field broadly, we did not focus on V2G applications in a specific vehicle class but instead across all vehicle classes. This means our analysis may miss more specific technical applications.

### 3. The technical dynamics to V2G research: renewables, grids, and batteries

Before we delve into lacunae within the domain of V2G research, it is useful to identify what the V2G community does emphasize in its research. The most frequently analyzed topics center on four core areas, starting with the most frequent: renewable energy storage and integration, grid stability, batteries, and distribution services.

#### 3.1. Renewable energy storage and integration

Renewable energy integration was by far the most common topic: 42% of papers in the population touched upon the connection between V2G and renewable energy in some way (although as we will see, often in a manner disconnected from broader social or environmental benefits). Renewable energy integration was discussed in various scales, but a substantial portion was in terms of smaller domains, e.g. microgrids or islands (defined as a small grid network that can operate independently of a larger national grid), and cost reduction via renewable energy storage and arbitrage [37]. For example, several sources found that introducing V2G to a microgrid would decrease the cost of operation, reduce reliance on the outside grid and increase utilization of wind and solar [38, 39]. A study of the Canary Islands found that assuming a certain threshold of V2G

**Table 1.** Systematic review of V2G and VGI peer-reviewed studies, 2015–2017.

Database	Results for 'vehicle to grid'	Results for 'v2g' (additional)	Results for 'vehicle grid integration' (additional)	Results for 'VGI' (additional)	Total	Total after screening for relevance
Nature Publishing Group	0	0	0	0	0	0
American Association for the Advancement of Science	0	0	0	0	0	0
National Academies of Science	2	2	1	0	5	5
American Chemical Society	2	1	0	0	3	3
Royal Society of Chemistry	0	0	0	0	0	0
ScienceDirect [1]	81	20	2	1	104	102
JSTOR	0	0	0	0	0	0
Project Muse	0	0	0	0	0	0
Hein Online Law	4	0	1	0	5	5
Journal Library						
PubMed	0	1	0	0	1	1
SpringerLink	48	1	1	0	50	44
Taylor & Francis Online	21	3	0	0	24	24
Wiley Online Library	25	2	1	0	28	10
Sage Journals	6	0	0	0	6	2
EBSCOhost	1	0	0	0	1	1
Sustainability						
Total	190	30	6	1	227	197

Source: Authors.

usage in tandem with pumped hydro storage reduced energy dependence while also increasing renewable share of load and reducing carbon emissions [40]. On a larger but still national level, research suggested that V2G-capable PEVs could provide a significant stabilizing effect in the integration and utilization of 2 GW of wind power in Latvia [41]. Finally, on a system operator scale, a study noted that introducing V2G increases renewable energy development by 51 GW in the PJM Interconnection, an increase of nearly 30% compared to scenarios without V2G [42].

### 3.2. Grid stability and ancillary services

Transmission grid stability and ancillary services was the next most common topic, appearing in nearly 24% of papers. The vast majority of these papers focused on frequency regulation and peak load shaving as the central services that could be provided [43]. V2G was characterized as a comparatively advantageous means of peak load shaving, assuming peak shaving events lasted one hour or less per day [37]. One paper focused primarily on spinning reserves, noting that such an application more than offset the cost of additional load from PEV charging [44]. Other papers explored technical interconnection standards and practices, including ISO 15118, which structures high-level communication between EVs and their chargers or electric vehicle supply equipment (EVSE) [45]. As a communication standard, ISO 15118 aims to standardize the automatic authentication, authorization, flexible load control and billing procedure between EVs and EVSEs [46–51].

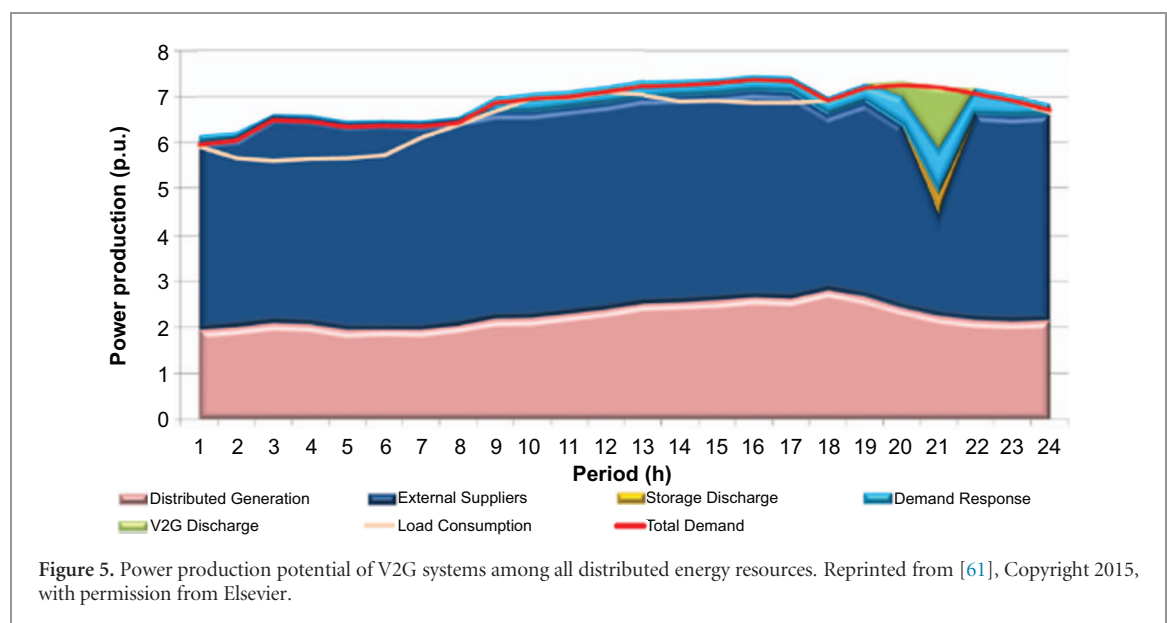
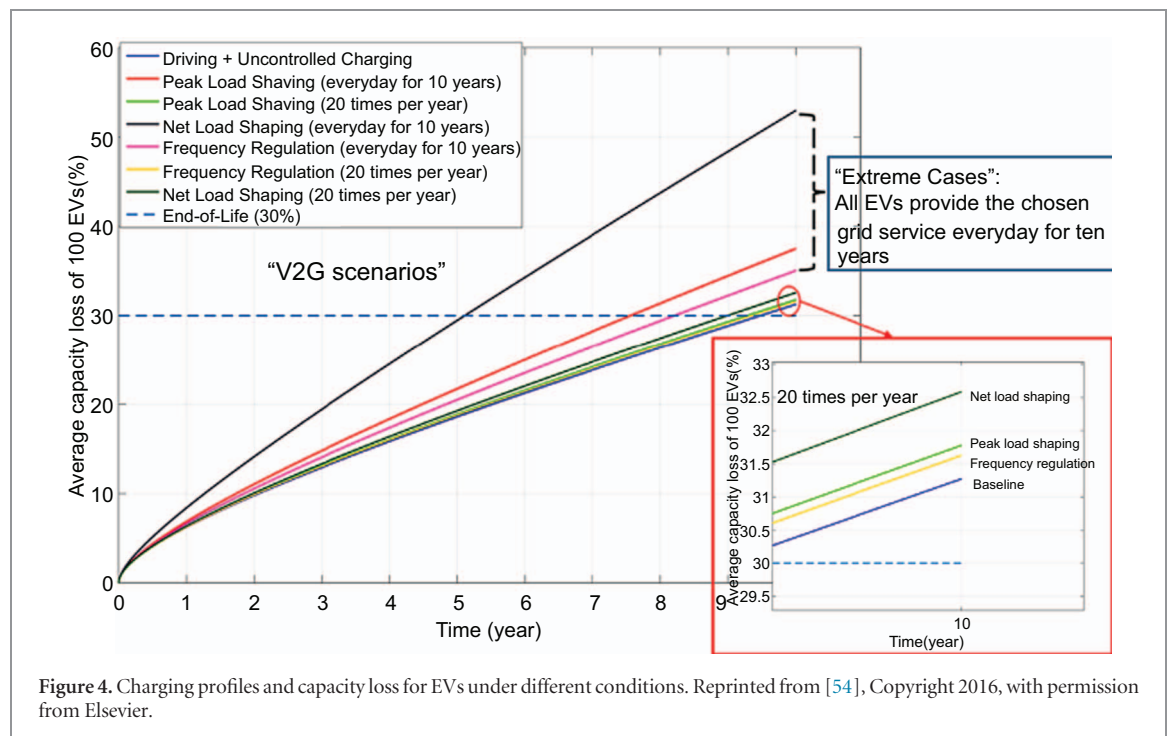
### 3.3. Battery charging and degradation

Slightly more than 18% of articles discussed battery degradation. Many studies presented the results of simulations or accelerated aging assessing battery performance, which will differ substantially based on battery chemistry, weather and temperature, and driving practices [52]. V2G systems place more use (and stress) on batteries, reducing their lifetime and resulting in early retirement of batteries [53]. One study found that average capacity losses in each frequency regulation event range from 0.0010%–0.0023% with different charger availability at home or work locations, corresponding to a cost of battery degradation as high as \$0.20–\$0.46 per charge (see figure 4) [54]. Some papers cut across the topics of grid services and batteries, connecting the provision of ancillary services to the cost of potential degradation of the battery, with many studies finding that degradation costs are a substantial barrier to the grid [55], while others find that degradation is minimal [54].

### 3.4. Distribution level services

Just over 15% of articles discussed distribution level services and benefits that V2G could provide. The topics within the distribution network were varied, but included voltage support and power quality, peak shaving and grid planning, and reducing congestion on the distribution network (see figure 5). Several articles identified the potential for V2G to cost-effectively improve power quality [56], including specifically voltage support [57]. Other papers looked at using V2G to control peak power supply to both more actively manage load curves [58] as well as to avoid critical situations [59]. Only a few of the papers discussed the





possible use of V2G to reduce congestion on the local grid. For example, one study found that using V2G can substantially reduce the probability of line congestion and voltage violations, by approximately 20 percentage points [60].

#### 4. Where is society? Neglected environmental, social, and human elements

Although discussions of the renewable energy, grid, and battery dimensions of V2G have their merit, in this section we argue that the field of research needs to move beyond technical topics and methods. For instance, whereas topics such as renewable energy storage were

mentioned in almost half of the articles we systematically reviewed, social acceptance, consumer norms and informing consumers were represented in less than 3%. Methodologically, the top three approaches across the population of articles were quantitative models, desk-based literature reviews, and having no explicit research design at all—reflecting a total of 80% of methods employed. By contrast, research designs based on experiments constituted only 6% of the papers, surveys 1.3%, and qualitative methods as a whole (interviews, focus groups, diaries, observation) only 0.9%. Less than one out of three studies analyzed had a case study, and only 3% of articles had comparative case study analysis.

With that in mind, this section of the paper argues for a broadening of focus to at least eight other areas: (1)

Table 2. Summary of eight underexamined topics in V2G research.

Dimension	Proportion of selection of articles ( $n = 197$ )	Example(s)
Environmental performance	10% (carbon emissions) and 2.5% (air pollution)	Assessing the V2G specific benefits of climate change mitigation or the displacement of noxious air pollution such as particulate matter or acid rain.
Financing and business models	4.6%	Monetizing the market value of V2G services, mechanisms by which businesses can capture those services, and identifying market segments.
User behavior	2.1% (consumer attitudes), 1.1% (range anxiety), 0.5% (information and education)	Examining the social acceptance of V2G technologies, driver concerns over battery range or degradation, and recommendations for better informing or educating users.
Natural resource use	1.0%	Studying the natural resource inputs (materials, minerals) with V2G, lifecycle assessments of externalities.
Visions and narratives	0.5%	Investigating the stories and imaginaries surrounding V2G, as well as hype cycles and expectations.
Social justice concerns	0%	Considering equity in the distribution of V2G costs and benefits, or displacement and exclusion in adoption patterns.
Gender norms	0%	Exploring the ways that gender norms, values, and routines affect V2G purchasing and driving.
Urban resilience	0%	Identifying V2G pathways on adaptive capacity and community resilience.

environmental performance, (2) financing and business models, (3) user behavior, (4) natural resource use, (5) visions and narratives, (6) social justice concerns, (7) gender norms, and (8) urban resilience. Table 2 provides an overview of these topics.

#### 4.1. Environmental performance

Interestingly, climate change and air pollution—two of the arguably most significant potential societal benefits to V2G technology—were mentioned infrequently. And much of the time, research that mentioned environmental benefits was not focused on V2G, but instead explored electric mobility more generally.

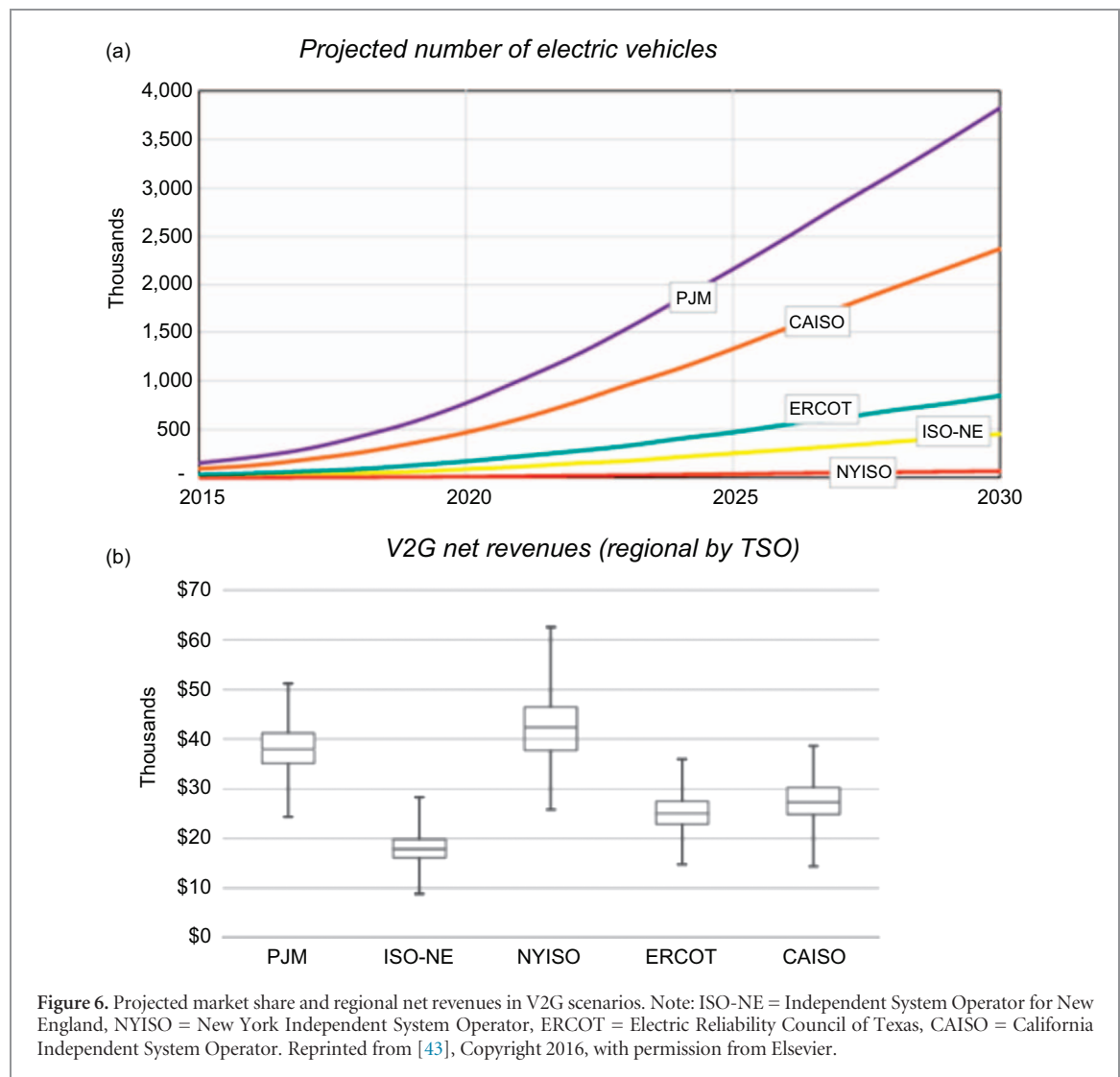
For instance, climate change was discussed in only 10% of articles in the population. V2G-capable PEVs can result in lower total emissions, particularly when compared to other alternatives [62]. Climate change benefits can accrue via the general electrification of transport, controlled charging to avoid high carbon electricity sources, decarbonization of the ancillary service markets, or peak shaving of high carbon electricity sources. Nonetheless, the net carbon benefits of V2G were only discussed in a handful of articles. Such studies suggest that the carbon benefits of V2G are dependent on various factors, especially the assumed generation mix of the electricity grid. One study finds that more than 8% of PEVs would need to participate in V2G in order for the emissions savings from V2G to outweigh the additional electricity-based emissions as a result of charging the PEVs—though this study does not account for the avoided gasoline emissions [63]. Similarly V2G-capable PEVs had the potential to reduce carbon emissions compared to a conventional gasoline vehicle by up to 59%, assuming optimized charging schedules [64]. In some electricity grids with higher CO<sub>2</sub>-intensity electricity and no climate policy, V2G providing load shaving services might actually increase total carbon emissions [64].

Though air pollution is another central impetus to electrify transportation and develop V2G technology, it was discussed in only about 2% of the population. Weis *et al* created a dispatch model to estimate the air emissions costs and benefits of different charging schemes [65]. Only two other studies focused on the monetization of health externalities in finding cost optimum penetrations of V2G-capable EVs, both in terms of optimal levels of electrified transportation, but also in that V2G could decrease air pollution emissions from the electricity sector [42, 66]. Another study only loosely discussing V2G mentioned air pollution emissions in the context of optimizing charging station site selection for PEVs [67], while a fifth focused on the potential for particulate matter emission reductions purely from a transportation perspective, noting that PEVs could decrease emissions by 34% by 2035 [68]. Yet, none of these papers focused exclusively or even primarily on the health impacts of V2G-capable EVs.

#### 4.2. Financing and business models

Only 4.6% of articles in the sample assessed financing or business and investment dimensions to V2G. Some of these focused on how to monetize and capture the value to the various types of grid services V2G can provide, including: active power regulation, supporting reactive power, load balancing by valley fillings, current harmonics filtering, peak load shaving, reduction in utility operating cost and overall cost of service, improved load factors, and the tracking of variable renewable energy resources [69]. In addition to these reliability and grid stability benefits, secondary environmental benefits, financial benefits, and increased participation in the electricity system could also be monetized [70].

Within the population we reviewed, one integrated modeling assessment of V2G pathways across various transmission systems operators in the United States



noted that projected revenues per vehicle could range between a mean of \$18 000–\$42 000 over the 16 year lifetime of the vehicle, depending on assumptions (see figure 6) [43]. It noted that V2G adopters providing regulation services in the New York Independent Service Operator region will have an average net revenue of \$42 000 during 16 years, and this number may vary from \$26 000–\$62 000 given the level of uncertainty with respect to capacity payments, energy payments, and battery unit prices. The PJM<sup>6</sup> region has an average net revenue close to that of the New York Independent Service Operator region, but its maximum value is relatively lower at \$51 000. The Electric Reliability Council of Texas and California Independent System Operator regions have similar net revenue projections at about \$25 000–\$28 000 on average, and the Independent System Operator for New England region's average net revenue is less than \$20 000. In some of these situations, the value and revenue from

offering V2G services more than offsets the purchase price of the vehicle. Another assessment in Denmark estimated that V2G would result in yearly energy cost savings per household of 8% to 20%; [71] yet another simulation calculated a 7% reduction in cost due to V2G in terms of annual travel expenditures [72]. In the United Kingdom, a pool of 30 V2G EVs at a science park was projected to create an estimated yearly savings of around £3500, including infrastructure costs [73].

Similarly, another study monetized the value of V2G integration in terms of day-ahead scheduling for electric power systems. It noted that fleets of EVs could reduce daily operational costs for electric supply utilities by about \$92 000 a day, or 3% of revenues, with most of this value coming from a reduction or shift of peak loads [74]. One review of smart grid business models noted that almost half of the articles surveyed (49%) discussed V2G and G2V services for consumers, system operators, or service aggregators, as table 3 summarizes [70].

However, the implications from these findings were challenged by other studies within the review. One assessment—a simulation of utilizing 5000 V2G enabled PEVs at parking lots—argued that more than

<sup>6</sup> PJM is a regional transmission organization coordinating electricity markets across Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia.

Table 3. Consumer, system operator, and aggregator financial value of V2G services.

	Value for consumer	Value for system operator	Value for service provider or aggregator
V2G and G2V services	<i>Lower prices:</i> Reduced prices for energy, electricity, batteries, or parking	<i>Lower costs:</i> Reduced system costs	<i>Lower costs:</i> Reduced costs for energy provision
	<i>Additional revenue:</i> financial streams generated from offering energy and ancillary services	<i>Improved reliability:</i> Access to improved regulation services, improved grid stability, improved leveling of load and management of intermittent supply	<i>Additional revenue:</i> Creation of revenues and profits via facilitating V2G
Demand response services	<i>Lowers consumption:</i> lower levels of demand and electricity bills	<i>Lowers congestion:</i> Fewer congestion costs, energy losses, or operating reserves, reduced need to invest in transmission lines or network improvements	<i>Lowers congestion:</i> lower plant investments by lowering peak demand, lower spot price volatility
	<i>Improves quality:</i> greater power quality, improved choice for managing electricity costs, greater control over bills, lower load shedding	<i>Cheaper system services:</i> access to improved regulation services, flatter load curves, greater network reliability	<i>Cheaper system services:</i> Revenue from offering ancillary services and lower sourcing costs for electricity retailers
Renewable energy integration and storage services	<i>Connecting renewables:</i> can generate financing for installing solar energy systems, cheaper electricity and profitable sales of electricity	<i>Connecting renewables:</i> could receive brokerage fees for carbon or renewable energy credits, tracking and monitoring	<i>Connecting renewables:</i> earns interest on loans for connecting V2G systems, can benefit from feed-in tariffs
	<i>Integrating renewables:</i> dynamic pricing lowers electricity bills, distributed generators receive fees for balancing services	<i>Integrating renewables:</i> dynamic pricing reduces peak load, lowers grid capacity requirements, profits generated from voltage management services, storage decreases peak demand and system costs, enhances system reliability and quality of supply	<i>Integrating renewables:</i> dynamic pricing reduces peak load, generates profits from balancing services, combination of renewables and smart charging of electric vehicles improves financial attractiveness of those investments

Note V2G = vehicle-to-grid. G2V = grid-to-vehicle. Reprinted from [70], Copyright 2016, with permission from Elsevier.

half of the vehicles (52%) would cost more (in charging) than they would earn (in revenues) [75]. Another study using empirical electricity market data from Germany warned that, ‘simply selling energy to [P]EV owners results in substantially higher revenues than ancillary services such as frequency regulation... The times at which vehicles enter and leave garages follow stochastic processes and even if the chance is slim, the number of vehicles may be insufficient to supply the required amount of power at the time of a regulation incident [76].’ Another simulation looking at the United Kingdom’s Generic Distribution System concluded that V2G did not offer an opportunity for major financial savings, calculating daily savings of about £1 and concluding that ‘it may be argued that this is not a sufficient incentive for drivers to participate in such a scheme given the impact it may have on their vehicles battery life and availability [77].’

Despite this uncertainty, it remains likely that different market segments for V2G will exist. Although the V2G literature has not yet systematically explored this topic, insights from related studies looking only at PEVs

may be of use. Wolf *et al* utilized an agent based model of perceptions of PEVs in Germany and identified four differing ‘mobility types’ of comfort-orientated individualists, cost-oriented pragmatics, innovation-oriented progressives, and eco-oriented opinion leaders [78]. Lieven *et al* noted that decision-making criteria for PEV purchasers reflect at least five distinct markets: short and long distance day drivers, second vehicle drivers, family cars, commercial vehicles and taxis, leisure drivers, and off-roaders [79]. Pierre *et al* looked at early adopters or EV ‘pioneers’ in France and identified two classes of users, those with a pioneering, ecological spirit and those who seize financial opportunities [80]. Ryghaug *et al* utilized focus groups and interviews with EV adopters in Norway and differentiated ordinary drivers from early adopting pioneers as well as late adopting laggards [81]. So far, these studies have analyzed PEVs generally, but not yet V2G, which could germinate entirely new classes of users and resulting market segments. Bailey and Axsen provide one exploration of potential PEV owner interest in enrollment in controlled charging

programs including V2G, finding significant heterogeneity in consumer valuation of cost savings versus environmental benefits [82]. Such market segments could translate into distinct business models; they also interrelate with the user behaviors we discuss in the next section.

#### 4.3. User behavior

The social acceptance of V2G technologies and attitudes and perceptions of drivers and other uses is a paramount concern for the successful diffusion of V2G (and electric mobility). Yet few studies in the sample looked at users and consumer behavior—consumer routines and norms were discussed in fewer than 2.1% of articles, range anxiety less than 1.1%, information and education for consumers less than 0.5%. This is striking given that there are areas of research in the PEV community where behavioral and environmental aspects have been studied with direct lessons for automotive manufacturers, policymakers, and electric utilities.

In short, the vast majority of studies in our population did not use empirical consumer data to explore consumer uptake of PEVs, or of consumer interest in voluntarily enrolling in a V2G program. One explanation could be that it is hard to elicit perceptions of something not yet widely used, only at the pilot stages, or in a phase of pre-commercialization—for example, qualitative research with a sample of mainstream car buyers find that they are even more confused about vehicle-grid-integration than about PEVs [83]. Further, in all research exploring consumer preferences for novel technologies there is a risk of measuring (inflated) expectations or hype rather than preferences informed by use [84]. Or, it could be that many researchers believe that V2G and VGI systems could be convenient and effortless to use; so that they do not conflict with attitudes or need user engagement. Thus, they may not deem it necessary to focus on them. Most of the modeling studies assume consumer ‘optimization’, often where PEV uptake and V2G enrollment reach 100%. In such studies, empirical data from actual (or potential) users is either nonexistent or anecdotal.

Yet mainstream vehicle buyers might have many concerns about V2G, including the potential costs, impacts on lifestyle, or just plain confusion about the concept [83]. As noted above, consumers might have a wide of variety of reasons to value (or not) V2G attributes, including potential environmental benefits, inconveniences of deferred PEV charging, and perceptions of potential battery degradation [82, 85]. Some researchers believe that the interaction between V2G events, battery state of charge, and consumer lifestyle or travel patterns could be particularly important. As Needell *et al* note: ‘Electric vehicles can contribute to climate change mitigation if coupled with decarbonized electricity, but only if vehicle range matches travelers’ needs. Evaluating electric vehicle range against a population’s needs is challenging because detailed

**Table 4.** Consumer concerns about electric vehicles in the United States.

Concern	Number of responses	%
Battery range	158	33
Cost	129	27
Charging infrastructure	83	17
Other	58	12
Reliability	47	10
Safety	6	1

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driving behavior must be taken into account’ [86]. It should be noted that consumer perceptions of range can vary dramatically when talking about range limited PEVs, notably BEVs, as opposed to PHEVs that have both a fossil-fuel powered engine and electric motor that can be powered by grid electricity. Given that several consumer surveys find that mainstream vehicle buyers are more likely to purchase PHEVs over BEVs, [87, 88] it is questionable as to how important range limitations may be in a future world of high PEV adoption.

However, the lacking focus on consumer travel patterns could be an important omission for some V2G scenarios focusing on BEVs, given that ‘range anxiety,’ or concerns over how far vehicle BEV can go between charges, could be of critical salience for adoption [89, 90]. Although practically ignored by the sample of V2G literature, two types of BEV range anxiety exist: one type is associated with inadequate battery level to complete a trip, the other is for a BEV being unsuited to a particular type of trip (one long distance, and/or outside of charging networks) that extends beyond the full range of the vehicle [91]. Although dated, one 2012 survey of drivers in the United States found that ‘battery range’ represented the single most important concern expressed about the BEVs, as table 4 summates, even a greater concern than ‘cost’ [92]. Another even older 2010 survey noted that 63% of respondents in the United States expressed serious concerns over the reliability and availability of local charging networks for BEVs [93].

#### 4.4. Natural resource use

Most V2G literature with an environmental focus assesses greenhouse gas emissions or air pollution, with an emphasis on direct impacts (i.e. local electricity supply, vehicle use). For example, only two papers in our selection of articles touched upon natural resource use explicitly: Pehlken *et al* examined the environmental impacts of cobalt demand and lithium battery use [94], and Zhao and Tatari conducted a lifecycle assessment of some externalities [95]. Natural resource dimensions such as materials, rare earth minerals [96], or lifecycle pollutants beyond carbon and air pollution (other toxics, water) are thus rarely studied.

However, the process of manufacturing EVs and batteries can be polluting. Indeed, Hawkins *et al* warn that manufacturing facilities for EVs produced



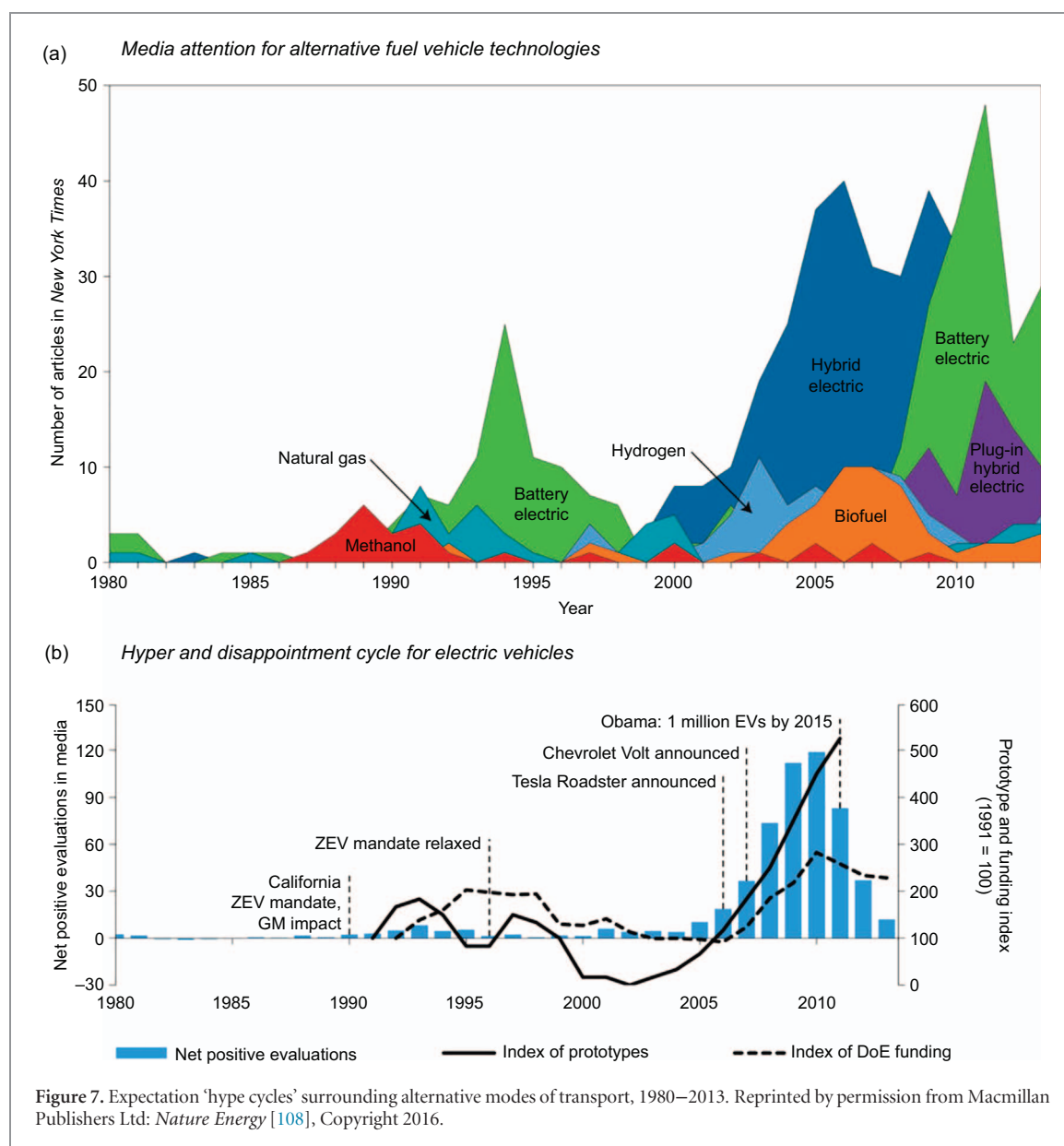


Figure 7. Expectation 'hype cycles' surrounding alternative modes of transport, 1980–2013. Reprinted by permission from Macmillan Publishers Ltd: *Nature Energy* [108], Copyright 2016.

more hazardous waste than conventional car factories [97]. An implication is that the heralded environmental benefits of an V2G transition—fewer greenhouse gas emissions and improved air quality in urban environments—may be traded off with any environmental damages stemming from mining operations, increased pollution from factories making EV components and toxic landfills and junkyards where obsolete models (and their batteries) end up [98]. Or put another way, the climate or environmental policies that might support a V2G transition should also consider upstream production practices, to assure a strongly net positive impact. Another natural resource issue is water. As a transition from internal combustion engines to V2G electric power is likely to increase the consumption of electricity, this could lead to negative impacts on water availability, especially because fossil fuel and nuclear power plants—which currently dominate the electricity generation sector—require large amounts of water for the production of steam and for cooling

processes [99]. The added water intensity associated with PEVs could make it difficult to electrify transport in regions where water is scarce—a prevalent condition in many large urban areas and arid regions across the globe [100]—although positive synergies could also occur, to the extent that V2G enables the integration of renewables and displacement of conventional water-intensive power plants.

#### 4.5. Visions and narratives

Only a single article in the population explicitly investigated the topic of visions, narratives, or rhetoric, focusing on 'sociotechnical imaginaries' for grid-connected EVs in Germany [101]. It analyzed the 'multiplicity of competing imagined futures of this technology' and sought to reveal the 'materiality, meaning, and morality' of the visions connected to electric mobility. The study identified at least two different rhetorical visions: a 'swarm' scenario lacking central control where distributed agents come to seamlessly

interact to create an interconnected, functional electricity and mobility system (tying together vehicles and decentralized sources of renewable electricity supply). This contrasts with the ‘autarky’ scenario where individuals come to enhance their autonomy, ownership, and control over both their vehicles and homes, using them to enhance self-sufficiency, mitigate emissions, and create financial opportunities.

However, despite the infrequency to which visions and narratives are analyzed within the population, in innovation studies there is now a well-established literature on the power of visions of the future. Visions, and the expectations they articulate, can motivate engineers and designers to initiate projects [102] and raise interest or investment from a wider range of stakeholders into a particular innovation, and thereby increase its legitimacy and uptake [103, 104]. Expectations are of great importance for the development of technologies as they stimulate, steer and coordinate action among actors as diverse as designers, managers, investors, sponsors, and politicians [105].

A related concept is that of a ‘hype cycle’ or ‘promise-disappointment cycle,’ an admittedly simple but visual representation of the ups and downs, peaks and troughs of technological expectations—which can be mapped out using media or document analysis of positive expectation statements for the new technology in question, as well as trends in R&D funding and patent activity [106, 107]. Here technologies are seen to move along a path from trigger, to a peak in expectations, then plummeting into a trough of disillusionment before eventually giving rise to a range of somewhat more modest applications, as figure 7 suggests, where we also see various technologies, including PEVs, exhibiting hype cycles historically. Melton *et al.*’s review of over 30 years of hype and disappointment for alternative-fuel vehicle technology adds that ‘hype can play an important role in supporting successful innovation activities,’ where low-carbon technology failure to date may largely be a result of the lack of strong climate and energy policy needed to support innovation to reaching mass market success [108]. This analysis did not cover V2G specific imaginaries and expectations, though the themes may be equally important for understanding the potential for V2G success in the mass market.

#### 4.6. Social justice concerns

One line of inquiry was never mentioned in our population of articles—that of ‘social justice’ or ‘energy justice.’ These terms describe various normative attempts to connect conceptions of distributive justice, procedural justice (due process), cosmopolitan justice, and justice as recognition to energy and climate issues such as transport planning or the equity or equality impacts of new technologies [109]. A social justice frame to energy and transport therefore involves burdens, or how the hazards of the energy system are disseminated throughout society; benefits,

or how access to energy or mobility services is distributed throughout society; procedures for ensuring that energy decision-making respects due process and representation; and recognition, that the marginalized or vulnerable have special consideration [110].

That such elements are not discussed within the sample is a notable gap, given that social justice concerns emerge as important considerations in any transition to a V2G system. Already, the consumption of mobility and transportation modes reflect, and may reinforce, patterns of inequality. In the United Kingdom, for instance, those in the highest income quintile travel nearly three times further than those in the lowest quintile [111]. Travel, as table 5 summarizes, connects with issues of income and class. As Wells adds, ‘mobility, or the lack thereof, has long been recognised as an important aspect of exclusion, inequality and poverty [112].’ Moreover, transportation infrastructure and technology developments often benefit middle and upper class denizens because: they cater to their transportation needs (the development of suburban highways, for instance); pollution and congestion often accumulate in poorer neighborhoods; and poor residents are more likely to be displaced or have their neighborhoods disrupted due to developments [113, 114].

Some of this research on equity has focused on PEVs, albeit not within the V2G community. Early adopters of PEVs tend to be both wealthy and older than ordinary drivers [116], and to utilize them as second cars so that drivers had another, conventional vehicle at home to offset concerns about range [117]. A stated preference survey conducted in the United Kingdom revealed that higher income groups are more likely to consider a PEV as a second vehicle [118]. In some cultures such as China, PEVs are perceived as an elite and luxury consumer technology [119].

Energy justice concerns therefore deserve a more prominent place in a future V2G research agenda. One could argue that V2G could help energy justice concerns by integrating wind and solar, and to push out dirtier forms of ancillary service participants. However, we also already know that PEVs shift pollution from local tailpipes to power plants, making it a transboundary issue as pollution shifts to more regional distribution patterns [120]. But how does a V2G configuration impact these trends? Also, greater battery wear and degradation could have justice implication in terms of where and how the externalities of battery manufacturing, and disposal and use, are distributed. It is also telling that very few authors within the population of V2G authors came from developing countries, meaning V2G was seldom connected to sustainable development and mobility options in the global south, particularly South America and Africa. Lastly, V2G automobiles as private cars still endorse a paradigm of private vehicle ownership, with a consequent impact on rates of diabetes, cardiovascular disease, and

Table 5. Income, poverty, and mobility in the United Kingdom.

	Lowest household income quintile (%)	Average household income quintile (%)	Highest household income quintile (%)
<b>Trips per person by mode</b>			
<i>Walking</i>	34	24	18
<i>Car</i>	46	63	71
<i>Bus and coach</i>	13	6	3
<i>Rail</i>	2	2	5
<i>Other</i>	5	4	3
<b>Distance per person per year (miles travelled)</b>			
<i>Walking</i>	5	3	2
<i>Car</i>	69	80	79
<i>Bus and coach</i>	13	5	2
<i>Rail</i>	7	7	11
<i>Other</i>	6	5	6
<b>Total CO<sub>2</sub> emissions</b>	690 kg	1250 kg	2030 kg

Source: Modified from [115]. Note: Other includes bicycle, other private transport, taxi, minicab, and other public transport. Data is based on the 2007 National Travel Survey.

obesity among owners relative to those who walk or take public transport [121]. In a world of limited resources and competing priorities, is V2G more or less just than these alternate forms of mobility such as cycling or walking?

#### 4.7. Gender norms

Another line of inquiry—we coded for it and it was never mentioned in our selection of articles—is that of gender and gendered norms of identity. At the turn of the previous century, for example, the early electric car was perceived as particularly suitable for (white) women, given its operational ease, cleanliness, and limited range [122]. Electric vehicles thus came to be associated with lack of power and femininity, so much that many women drivers were laughed and hooted at by men operating gasoline vehicles. Manufacturers exploited such prevailing gender norms when they tried to frame cars as masculine [123]. Gender, therefore, can exert a powerful influence on perceptions as well as the adoption of V2G enabled cars. For example, a survey of Canadian car buyers finds that early electric vehicle buyers are overwhelmingly male (81%), especially Tesla owners, though among conventional vehicle owners, females express slightly greater interest in being the ‘next’ electric vehicle buyers [124]. How might gendered norms affect third parties ‘controlling’ a vehicle to provide grid services? Or what type of marketing approach would have the most appeal and effectiveness in convincing mothers to become active providers of V2G services? The underrepresented number of women writing V2G articles only underscores the critical need of more rigorously researching this topic.

#### 4.8. Urban resilience

A final understudied domain is the intersection between investments in V2G sociotechnical systems and urban resilience, that is, the capacity of urban areas to adapt to different shocks, such as climate change. No research within the selection of articles assessed

how V2G systems might impact the ability of urban communities, local authorities, or small and medium enterprises to build resilience in the face of sustainability challenges, or operate during natural disasters, which are becoming more frequent and intense [125]. A handful of papers discussed EVs or V2G in the context of urban areas, but only the extent of transportation demand or to focus on urban grids; a few other papers investigated how V2G could improve the reliability of urban grids, which theoretically could be connected to community resilience, but never made the link explicit. Similarly, although efforts at climate change mitigation (and air pollution abatement) were occasionally discussed, how V2G can synergize with, or tradeoff with, adaptation—building capacity to respond to the impacts of climate change—and disaster recovery was not.

Policies and programs for resilience and recovery can enhance humanity’s capacity to predict, and then effectively manage, the expected impacts of climate change (and other challenges) [126–128]. Whether V2G systems compete with or complement adaptation remains unknown. For instance, during major floods or blackouts, passenger vehicles such as BEVs would not be able to recharge and could become a liability more than an asset. On the other hand, if the batteries in such vehicles were charged before the disaster, they could potentially provide a temporary source of electricity for a household [129]. In non-disaster situations, V2G can reduce peak congestion on electric power grids and substitute for new capacity additions, but it could also directly cut into the profitability of building new natural gas peaking plants (lowering the financial resilience of traditional electric utilities and some sectors of the economy) and potentially interfering with heat supply in areas with combined heat and power or district heating. Such potential tradeoffs illustrate how implementing some aspects of a V2G transition could erode community, economy, or national resilience in other dimensions (or at other scales).

## 5. Conclusion

The adoption of V2G systems could offer a valuable source of energy storage, facilitate the accelerated uptake of renewable sources of energy, spawn a variety of transmission and distribution grid services, and enhance innovation and research on batteries. It is therefore a topic deserving of strong, robust technical (and economic) work. However, here we argue that such a V2G research agenda remains incomplete, and that meaningful sociotechnical barriers remain. Although the optimal mix is hard to discern, the share of studies that focus on technical matters and rely on technical methods seems too large and imbalanced—as demonstrated by the many socially-relevant research questions that remain unexplored. The community needs to embrace more multi-method, cross-comparative, integrated and holistic research that focuses on humans and social considerations. We propose that some of these considerations ought to focus on the air pollution and climate change benefits unique to V2G, an area that remains under-studied. Business models, market segments, and the complexity of user motivations is all but ignored within the recent V2G literature. Topics such as natural resource use (mentioned twice in our selection of articles), rhetorical visions and hype cycles (mentioned once), and energy justice as well as gender norms and urban resilience (mentioned not at all) are virtually nonexistent.

These research gaps could hold important implications for present and future development of V2G. Efforts to design V2G systems purely on a cost-minimization basis, without consideration of climate or environmental goals, could actually increase environmental impacts in some regions [130], producing incentives to use more fossil fuel based source of electricity. Further neglect of consumer research concerning potential enrollment in V2G programs could also encourage unrealistically positive expectations among policymakers and industry—if they are instead only informed by models that assume all consumers are complacent system ‘optimizers’. Because the limited amount of V2G consumer research to date indicates the potential for consumer resistance due to concerns about trust and battery degradation [82], V2G proponents could miss out on opportunities to anticipate such opposition and to develop methods to cultivate acceptance. Perhaps lessons can be learned from various smart meter rollout programs that were met with varying degrees of social opposition or ambivalence, due in part to an initial lack of consumer focus or inflated expectations [131, 132]. Similarly, advancing V2G research into concerns regarding other environmental and resource impacts (beyond climate and air pollution), visions and narratives, social justice, gender norms and urban resilience can only aid with successful planning for a widespread transition to V2G systems, mitigating the potential for negative side-effects. Furthermore, emerging V2G pilot projects could perhaps

be even more valuable if designed to collect insight into all of the social themes we note here, in addition to the functioning of a piloted system or simulations about batteries, control systems, and other technical elements. Thus, these research gaps need to be addressed if V2G, and vehicle-grid integration more broadly, is to achieve the societal transition its advocates seek.


## Acknowledgments

The authors are appreciative to the Research Councils United Kingdom (RCUK) Energy Program Grant EP/K011790/1 ‘Center on Innovation and Energy Demand,’ the Danish Council for Independent Research (DFF) Sapere Aude Grant 4182-00033 B ‘Societal Implications of a Vehicle-to-Grid Transition in Northern Europe,’ which have supported elements of the work reported here. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of RCUK Energy Program or the DFF.

## ORCID iDs

Benjamin K Sovacool  <https://orcid.org/0000-0002-4794-9403>

Lance Noel  <https://orcid.org/0000-0001-9396-2361>

Willett Kempton  <https://orcid.org/0000-0002-7284-8954>

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